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The Age of the Universe: Concordance

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ABSTRACT

Arguments on the Age of the Universe, t_u, are reviewed. The four independent age determination techniques are:

(1) Dynamics (Hubble Age and deceleration);
(2) Oldest stars (globular clusters);
(3) Radioactive dating (nucleocosmochronology);
(4) White dwarf cooling (age of the disk).

While discussing all four, this review will concentrate more on nucleocosmochronology due in part to recent possible controversies there. It is shown that all four techniques are in general agreement, which is an independent argument in support of a catastrophic creation event such as the Big Bang. It is shown that the most consistent range of cosmological ages is for $12 \lesssim t_u \lesssim 17 Gyr$. It is argued that the upper bound from white dwarf cooling is only $\sim 10 Gyr$ due to the disk of the Gaxaxy probably forming several Gyr after the Big Bang itself. Only values of the Hubble constant, $H_o \lesssim 60 km/sec/Mpc$, are consistent with the other age arguments if the universe is at its critical density. An interesting exception to this limit is noted for the case of a domain wall dominated universe where ages as large as $2/H_o$ are possible.

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Introduction

The age of the universe can be estimated by four independent means:

1. Dynamics (Hubble age and deceleration)
2. Oldest Stars (globular clusters)
3. Radioactive Dating (nucleocosmochronology)
4. White Dwarf Cooling (age of the disk)

All four of these techniques have been discussed at this Institut d'Astrophysique symposium on "datation." This paper will focus on radioactive dating and on the concordance of the four techniques. We will see that despite much work over the last couple of decades, the basic picture is still a total age of about 15 Gyr with an uncertainty of several Gyr. While trends come and go in each technique, the uncertainties continue to allow this range of concordance. If $\Omega = 1$, as most cosmologists believe, then concordance does seem to favor small values for H_o ($\lesssim 60 km/sec/Mpc$). Furthermore, the age of the disk may really be significantly lower than the age of the universe ($t_{disk} \lesssim 10 Gyr$), which may be telling us something quite interesting about galaxy formation.

As to nucleochronology itself, much attention has focused on new production estimates and on the measurements in stars, but when all the smoke clears away, the basic relatively independent model conclusion remains solid, namely, a strong lower bound of about 9 Gyr from the lowest mean age and a "best-fit" galactic evolution dependent age of 12 to 18 Gyr.

Although all of the techniques are reviewed in other papers in this proceedings, for completeness and to show the author's viewpoint, this paper will briefly describe the results of each of the four techniques. However, the discussion of nucleochronology will be somewhat more detailed. The paper will then discuss the problems of concordance and make its conclusions.

The Age from Dynamics

The use of the Hubble constant to determine an age is the most quoted and least accurate of all the age determination methods. Detailed references are given in other papers in this volume, so they won't be repeated here. Let us merely note that astronomers continue to get values ranging from $H_o \sim 100 km/sec/Mpc$ down to values near $H_o \sim 40 km/sec/Mpc$. The higher values tend to come from people using techniques like Tulley-Fisher, whereas the smaller values come from people using supernovae. A critical question tends to be the accuracy of intermediate distance calibrators and the correction for infall into the Virgo cluster. Most of us can't see anything wrong at face value with the Tulley-Fisher techniques other than a possible susceptibility to the so-called Malmquist bias.

However, many physicists have a certain fondness for the use of Type-I supernovae as standard candles. Type I's seem to be due to the detonation of a C-O white dwarf star converting its C-O to Fe. Such a model has a physical relationship between its luminosity and basic nuclear quantities that can be measured in the lab. Current best-fit models (c.f. Nomoto) tend to convert about $0.7M\odot$ of C-O, which yields $H_o \sim 60km/sec/Mpc$. However, even in the extreme where the entire $1.4M\odot$ Chandrasekhar mass is burned, H_o is never below $38km/sec/Mpc$. Sandage and Tammann's empirical calibrations which ignore the nuclear mechanism yield $H_o \sim 42km/sec/Mpc$, which fall within the theoretically allowed range and correspond to almost complete burning of a Chandrasekhar core. While selecting between 42 and 60 is still a matter of choice, it does seem that values less than 38 can be reliably excluded. Why these numbers disagree so much with the best Tulley-Fisher determinations of about 80 remains to be understood.

Age, t_u, is related to H_o by:

$$t_u = \frac{f(\Omega)}{H_o} \tag{1}$$

where for standard matter-dominated models with $\Lambda = 0$,

$$f(\Omega) = \begin{cases} 1 & \Omega = 0 \\ 2/3 & \Omega = 1 \\ \sim 0.5 & \Omega = 4 \end{cases}$$

and smoothly varies between those values. The parameter Ω is the cosmological density $10Gyr$ parameter. A range of $40 \lesssim H_o \lesssim 100km/sec/Mpc$ yields $10Gyr \lesssim 1/H_o \lesssim 25Gyr$.

From dynamics alone we can put an upper limit on Ω by limiting the deceleration parameter q_o. From limits on the deviations of the redshift-magnitude diagrams at high redshift, we know that $q \lesssim 2$ (for zero cosmological constant $\Omega = 2q_o$. Thus we can argue that $\Omega \lesssim 4$ or that $f(\Omega) \gtrsim 0.5$. Therefore, from dynamics alone, with no further input, we can only conclude that

$$5 \lesssim t_u \lesssim 25Gyr \tag{2}$$

Since the lower bound here could also be obtained from the age of the earth, it is clear that the dynamical technique is not overly restrictive unless one could somehow decide between the supernova approach and Tulley-Fisher. Hopefully some of this dispersion should collapse when the Hubble space telescope flies and one can use cephieds in the Virgo cluster to remove many of the uncertainties in the intermediate distance calibrators.

An interesting loophole in the $t_u - H_o$ relationship occurs in a domain wall dominated universe. Hill, Schramm and Fry (1989) have argued that late-time phase transitions can produce domain walls which could generate the large-scale structure of the universe. The energy density in walls scales is $\sim 1/R^{1+\epsilon}$ where ϵ is dependent on wall evolution. For $0 \lesssim \epsilon \lesssim 1$, the resluting $t_u - H_o$ relationship for $(\Omega = 1)$ is $t_u = \frac{f'}{H_o}$ where $1 \lesssim f' \lesssim 2$ (c.f. Massarotti 1989).

Thus, high values of H_o can be consistent with high ages without invoking the cosmological constant if the universe is wall-dominated. (Such models also stretch out the age vs. redshift relationship, enabling longer times for galaxy formation.) Press, Ryden and Spergel (1989) have shown that $\lambda\phi^4$ wall models evolve to single horizon-size walls and thus are ruled out by the microwave isotropy. However, Hill, Schramm and Widrow (1989) show that sine-Gordon walls or walls from multiple minima avoid such problems, as do the texture models of Turok (1989).

The Age from the Oldest Stars

Globular cluster dating is an ancient and honorable profession. The basic age comes from determining how long it takes for low mass stars to burn their core hydrogen and thereby move off the main sequence. The central temperature of such stars is determined by their composition and the degree of mixing. While there has certainly been some static as to what is the dispersion between the age of the youngest versus the oldest globular cluster in a given calculation, there is a surprising convergence on the age of the oldest clusters. Since the age of the very oldest cluster is the critical cosmological question, it is really somewhat of a red herring as to how much less the youngest cluster may be. The convergence on the age of the oldest does require a consistency of assumptions about primordial Helium and metalicity (including O/Fe). Difference between different groups can be explained away once agreement is made on these assumptions. For example, Sandage's oldest ages of 18-19 Gyr and Iben's of 16-17 Gyr are consistent if the same Helium is used. (The lower range is more consistent with the current primordial Helium measurements of Pagel, 1989.) Another decrease of a billion years occurs if O/Fe is assumed high as current observations show. The best ages for the oldest globular clusters seem to be around 16 Gyr with a generous spread of $\pm 3 Gyr$ allowed. It should be noted that most other variations in assumptions, other than the compositional ones already mentioned, tend to go towards longer rather than shorter ages. For example, any mixing will increase the age since the standard model assumes a radiative non-mixed core. Mixing brings in more otherwise unburned material so that it takes longer to deplete the core's hydrogen.

The question of the range in age of globulars is important for relating globular ages to the ages of the disk and for models of cluster and galaxy formation. Whether or not the age spread is less than 1 Gyr or more like 5 Gyr doesn't change the basic point that the oldest globulars are 16 ± 3 Gyr.

Since in principle globulars can form within $\lesssim 10^8$yr of the Big Bang, we can use the age of the oldest globulars to argue that

$$t_u \sim 16 \pm 3Gyr \tag{3}$$

Of course, some models may take up to a Gyr to form the first globulars, but that is still in the allowed noise window.

White Dwarf Cooling Ages

The newest addition to age determination techniques is white dwarf cooling rates. The point that there is a paucity of cool white dwarfs can be used to set a limit on the age of the disk of our Galaxy. Of course, this age is dependent on assumptions about the rate of cooling of single white dwarfs, the initial mass function and time dependence of star formation rates and the estimation of what volume of space has been fully surveyed. While the paucity problem has been known for some time, the first comprehensive look at the age implications was Winget et al. They argued that the age of the disk was $t_d \lesssim 10Gyr$. To escape this bound one must argue that the assumptions are wrong in one way or another. One must be careful in relating this bound to the age of the universe. Clearly, it is some sort of lower limit, but the quesiton is: how long did it take to form the Galactic disk? One possible resolution of this might come from looking at cool white dwarfs in the halo. Unfortunately, the data is still sparse, but there is some indication of lower temperature ones, thus implying a longer age for the halos. A further argument on an extended time span between the Big Bang and disk formation is the difference between this age and the globular cluster ages. Another recent indication that the disk may form late comes from the observations of Gunn (1989) and York (1989) who each argue that disks do not seem to exist at redshifts $Z \sim 1$. Since the matter era age at redshift $Z(\Omega = 1)$ is

$$t_z \sim \frac{t_u}{(1+Z)^{3/2}} \tag{4}$$

the Gunn/York observations mean disks did not form until $\frac{t_u}{3}$.
For $t_u \sim 15Gyr$, this yields $t_d \sim 10Gyr$, consistent with the white dwarf arguments.

Nucleocosmochronology

Nucleocosmochronology is the use of abundance and production ratios of radioactive nuclides coupled with information on the chemical evolution of the Galaxy to obtain information about time scales over which the solar system elements were formed. Typical estimates for the Galaxy's (and Universe's) age as determined from cosmochronology are of the order of 9 -18 Gyr (e.g. Meyer and Schramm, 1986). In recent years questions about the role of β-delayed fission in estimating actinide production ratios as well as uncertainties in ^{187}Re decay due to thermal enhancement and the discussion of Th/Nd abundances in stars have obfuscated some of the limits one can obtain. In particular, we note that the formalism of Schramm and Wasserburg (1970) as modified by Meyer and Schramm (1986) continues to provide firm bounds on the mean age of the heavy elements. In fact, Th/U provides a firm lower limit to the age and Re/OS a firm upper limit. These limits are based solely on nuclear physics inputs and abundance determinations. To extend these mean age limits to a total age limit requires some galactic evolution input. However, as Reeves and Johns (1976) first showed, and as Meyer and Schramm (1986) developed further, one can use chronometers to constrain Galactic evolution models and thereby further restrict the age from the simple mean age limits of Schramm and Wasserburg. To try to push further on such ranges and give ages to $\pm 1 Gyr$ accuracy, as some authors have done, always necessitates making some very explicit assumptions about Galactic evolution beyond the pure chronometric arguments. At the present time such model-dependent ages are not fully justified and should probably not be used as arguments to question (or support) cosmological models.

Let us review what can be said from the nuclear physics without making too many specific model-dependent assumptions.

The linearized equation for the time dependence of the abundance N_i of nuclide i in the interstellar medium of the Galaxy (Tinsley 1975; see also Hainebach and Schramm 1977 and Symbalisty and Schramm 1981) is

$$\frac{dN_i(t)}{dt} = -\lambda_i N_i(t) - w(t) N_i(t) = P_i \psi(t), \tag{5}$$

where λ is the decay rate of nuclide i, $w(t)$ is a time-dependent parameter representing the rate of movement of metals into and out of the interstellar medium for resons other than decay, $\psi(t)$ is the amount of mass going into stars per unit time, and P_i is the number of nuclei i produced per unit mass going into stars.

It is now possible to solve for the abundance N_i of nuclide i at a given time by integration of equation (5). This is done in the context of the scenario for evolution of the material making up the solar system shown in the figure. In the figure, T is the time of the last event contributing to formation of the elements going into the solar system, Δ is the time interval between this last nucleosynthetic event and the solidification of the solar system solid bodies, and $t_{ss}(= 4.55$ Gyr) is the age of these solid bodies. In this scenario, Δ is a free decay period for the elements, and, consequently, we might choose to measure meteoritic abundance back to $t = T$. Meteoritic material is a closed system only after time $t + \Delta$. This material thus gives abundances at times as early as $T + \Delta$ with minimal uncertainty due to chemical fractionation, but not before. Integration of the equation for

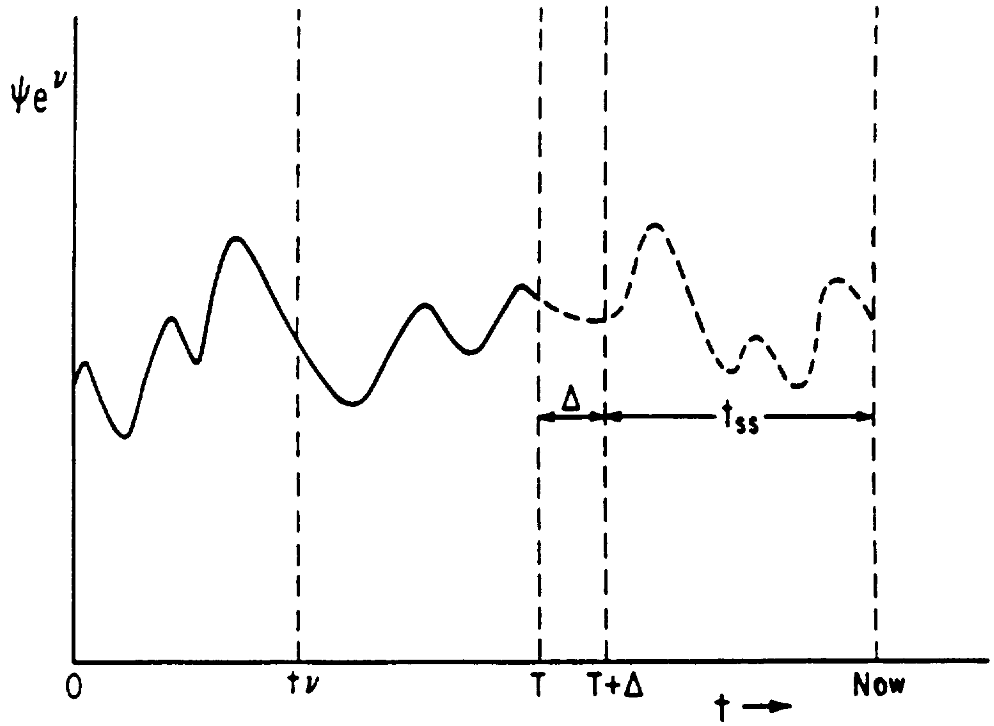

Figure 1. Schematic diagram showing the effective nucleosynthesis rate as a function of time. The quantity T is the total duration of nucleosynthesis, and t_ν is the mean time for the formation of the elements; Δ is the time interval between the end of nucleosynthesis and solidification of solar system bodies; t_{ss} is the age of the solar system solid bodies. The total age of the elements is $T + \Delta + T_{ss}$.

time $t = 0$ to $t = T$ followed by free decay over an interval Δ, yields

$$N_i(T + \Delta) = P_i exp(-\lambda_i \Delta) exp[-\lambda_i T - \nu(T)] \int_o^t \psi(t) exp[\lambda_i t + \nu(t) dt, \qquad (6)$$

where

$$\nu(t) = \int_o^t \omega(\xi) d\xi,$$

and we have assumed P_i to be independent of time.

Age estimates from radionuclides are obtained first by expansion of the normalized effective nucleosynthesis rate $\phi(t)$, defined as

$$\phi(t) \equiv \frac{\psi e^{\nu}}{\int_o^t \psi \epsilon^{\nu} dt} \qquad (7)$$

in moments μ (defined below) about the mean time for formation fo the elements t_ν, given by

$$t_\nu = \int_o^t \phi(t) dt. \qquad (8)$$

With this mean time, the moments μ are defined as

$$\mu_n \equiv \int_o^t (t - t_\nu)^n \phi(t) dt. \qquad (9)$$

Meyer and Schramm (1986) find (analagously to Schramm and Wasserburg 1970) an expression for the mean age of the elements as measured back from $t = T$:

$$T - t_\nu = \Delta_{ij}^{max} - \Delta + \frac{(\lambda_i + \lambda_j)\mu_2}{2} + \frac{(\lambda_i^2 + \lambda_i \lambda_j + \lambda_j^2)\mu_3}{6}$$

$$+ \frac{1}{4}(\frac{\mu_4}{6} - m_2^2)(\frac{\lambda_i^4 - \lambda_j^4}{\lambda_i - \lambda_j}) + ..., \qquad (10)$$

where

$$\Delta_{ij}^{max} \equiv \frac{ln \frac{((P_i/P_j)}{N_i(T+\Delta)/N_j(T+\Delta))}}{\lambda_i - \lambda_j} \equiv \frac{lnR(i,j)}{\lambda_i - \lambda_j} (11)$$

and where the subscript j denotes a second radionuclide, distince from nuclide i.

Clearly, $T - t_\nu$ in equation (10) depends upon $\phi(t)$ through the moments μ; thus, we require some information about the effective nucleosynthesis rate if we are to continue. We may proceed in one of two fashions. We may choose a specific form or model for $\phi(t)$, in which case our results will be model-dependent. Alternatively, we may attempt to find external forms for $\phi(t)$ that will allow upper and lower limits to be placed on T essentially independently of any model for $\phi(t)$. This latter tack is the one described below.

First, we note that since the moment terms in equation (10) increase $T - t_\nu$ over $\Delta_{ij}^{max} - \Delta$, a lower limit on T is given by

$$T \gtrsim \Delta_{ij}^{max} - \Delta. \tag{12}$$

This is the long-lived limit of Schramm and Wasserburg and gives a model-independent lower limit on the time for nucleosynthesis. With knowledge of t_ν/T, the lower limit is pushed up to

$$T \gtrsim (1 - \frac{t_\nu}{T})^{-1}(\Delta^{max} - \Delta). \tag{13}$$

We derive limits on t_ν/T below. In principle, nucleochronology alone is not able to give a firm upper limit to an age as was demonstrated by Wasserburg, Schramm and Huneke (1969) who found consistent ages of $\gtrsim 10^{13}$ yrs. However, by using our constraints on average rates, some statements can be made, assuming that production was relatively smooth with no large gaps. For an upper limit on T, Meyer and Schramm find that

$$T \lesssim (1 - t_\nu/T)^{-1}(\Delta^{max} - \Delta)(1 + \epsilon) \tag{14}$$

where ϵ, which represents the correction to the long-lived limit, is constrained as

$$\epsilon \lesssim \frac{1}{8}(1 - t_\nu/T)^{-2}(\lambda_i + \lambda_j)(\Delta^{max} - \Delta)(1+\epsilon)^2$$

$$+\frac{5}{312}(1 - t_\nu/T)^{-3}(\lambda_i^2 = \lambda_i\lambda_j + \lambda_j^2)(\Delta^{,ax} - \Delta)^2(1+\epsilon)^3$$

$$+\frac{1}{288}(1 - t_\nu/T)^{-4}\frac{(\lambda_i^4 - \lambda_j^4}{\lambda_i - \lambda_j)}(\Delta^{max} - \Delta)^3(1+\epsilon)^4 + ... \tag{15}$$

With limits on t_v/T, equation (15) can be solved and, hence, limits on T will be available from equations (13) and (14). Meyer and Schramm develop such limits on t_ν/T in a method inspired by the work of Reeves and Johns (1976). First, an average nucleosynthesis rate $< \psi > r_i$, i over the interval $r_i \leq t \leq T$ is defined:

$$< \psi >_{r_{i,j}} \equiv \frac{\int_{r_i}^T \psi e^\nu e^{-\lambda_i(T-t)} dt}{\int_{r_i}^T e^{-\lambda_i(T-t)} dt}. \tag{16}$$

Then, through use of equation (16), analogous expressions for nuclides j, and variation over all possible intervals $r_i \lesssim t \lesssim T$ and $r_j \lesssim t \lesssim T$, it is found that

$$\frac{e^{(\lambda_i - \lambda_j)\Delta}}{R(i,j)} \frac{(1 - e^{-\lambda_j TT})}{(1 - e^{-\lambda_i T})} \frac{\lambda_i}{\lambda_j} \leq \frac{< \psi >_i}{< \psi >_j} \leq \frac{e^{(\lambda_i - \lambda_j)\Delta}}{R(i,j)} \frac{\lambda_i}{\lambda_j}, \tag{17}$$

where we choose T to be its smallest possible value, namely, that given by equation (12).

The ratio of average rates $< \psi >_i \; / < \psi >_j$ constrained in equation (17) is useful because it determines the general trend of ψe^ν over a few lifetimes of nuclide i. Thus, since $\lambda_i > \lambda_j$, if $< \psi e^\nu >_i \; / < \psi >_j \approx 1$, then ψe^ν was generally falling over a few times r_i, and if $< \psi >_i \; / < \psi >_j > 1$, then ψe^ν was generally rising over a few times r_i.

To obtain constraints on t_ν / T, we define $r(i,j)$ as the ratio $< \psi >_i \; / < \psi >_j$. We assume a set of m chronometers. We label the longest by $i = 1$, the next longest by $i = 2$, and so on, to the shortest-lived, labeled $i = m$. We then have as constraints on ψe^ν

$$\psi e^\nu = r(i,l) \text{ for } t_{i-1} \lesssim t \lesssim t_i,$$

where i runs from l to m, t_i is defined as

$$t_i = \frac{T}{r_i}(r_i - r_{i+!}),$$

and $t_m = T$.

From the above, constraints on t_ν / T are available, viz.,

$$\frac{t_v}{T} = \frac{1}{2} \frac{\sum_{i=1}^{m} r(i,l)[(r_i - r_i = 1)^2]}{r_i \sum_{j=1}^{m} r(j,l)(r_j - r_j + 1)}.$$

Use of upper limits on $r(i,j)$ give an upper limit on t_ν / T. For lower limits on t_ν / T, Meyer and Schramm choose to use two chronometers in a slightly different fashion to obtain

$$\frac{t_\nu}{T} = \frac{r(2,1) - \sqrt{r(2,1)}}{r(2,1) - 1}.$$

Use of lower limits on $r(2,1)$ gives lower limits on t_ν / T. Similarly, upper limits on $r(2,1)$ can give upper limits on t_ν / T.

With constraints on t_ν / T, we can, given the requisite input data, derive limits on T and T_{GAL} from the fact that

$$T_{GAL} = T + \Delta + t_{ss}.$$

We turn now to a discussion of the input data.

In Table 1 we present best estimates of decay rates, the ratios $R(i,j)$, and resulting Δ^{max} values for the Re/Os, Th/U, U/U, and Pu/U chronometric pairs. The text that follows gives a brief discussion of the uncertainty in these data.

A. Re/Os

The long-lived chronometric pair $^{187}Re/^{187}Os$ is unique because ^{187}Os is stable. Since $\lambda_j = 0$, and since $\Delta^{max} > \Delta$ (see Symbalisty and Schramm who find $\Delta \lesssim 0.2 Gyr$), we may write equation (15), through use of equation (11), as

$$\epsilon \lesssim \frac{1}{8}(1-\frac{t_\nu}{T})^{-2}[lnR(187,187)](1+e)^2 + \frac{5}{312}[(lnR(187,187)]^2(1+e)^3$$

$$+\frac{1}{288}(1-\frac{t_\nu}{T})^{-4}[lnR(187,187)]^3(1+e)^4 ... \qquad (18)$$

The only necessary data, then, are $R(187,187)$ and λ_{187} (to get $\Delta^{max}_{187,187}$). $R(187,187)$ is given by (Schramm 1974)

$$R(187,187) = 1 + \frac{(^{187}Os)c}{^{187}Re}, \qquad (19)$$

where $(^{187}Os)c$ is the r-process contribution to ^{187}Os.

Unfortunately, both $R(187,187)$ and λ_{187} are uncertain quantities. Bound state β-decay of ^{187}Re occurring due to astration may greatly enhance the decay rate over the lab rate (Takahashi and Yokoi 1982; Yokoi, Takahashi and Arnould 1983). Detailed galactic evolution models are thus required to determine the amount of astration of ^{187}Re and, consequently, the effective decay rate of ^{187}Re. This is difficult and uncertain work. We note instead that the effect of astration is always to increase λ_{187}. Thus, from equation (11) we obtain an upper limit on $\Delta^{max}_{187,187}$. We also emphasize that ϵ in equaiton (18) is independent of λ_{187}.

The uncertainty in $R(187,187)$ arises from two sources. First, a low-lying, excited nuclear state in ^{187}Os complicates the determination of $(^{187}Os)c$ (Fowler 1973; Holmes et al. 1976; Woosley and Fowler 1979). Second, s-process branchings in the $W - Os$ region (Arnould 1974; Arnould, Takahashi and Yokoi 1984) may contribute to the uncertainty in $R(187,187)$. The range on $R(187,187)$ found by Meyer and Schramm from the analaysis of Yokoi et al. and meteoritic data of Luck, Brick and Allegre (1980) is $1.06 \lesssim R(187,187) \lesssim 1.14$. The numbers of Arnould et al. lead Meyer and Schramm to the larger range $1.03 \lesssim R(187,187) \lesssim 1.23$. Meyer and Schramm rely mainly on the former range for $R(187,187)$, but also consider the effects of the latter range. Use of cross section data from Winters et al. (1980) and a best value for the cross section correction factor f_σ of 0.82 (Winters 1984) gives a best $R(187,187)$ of 1.12. The lab λ_{187} is $1.59^{+0.05}_{-0.04} x 10^{-11} yr^{-1}$ (Linder et al. 1986). The bottom line here is that one should not ignore ^{187}Re but use it as an upper bound.

Table 1

Cosmochronological Input Data and Paramaters		
Pair	$\lambda_i(Gyr^{-1})$	$\lambda_j(Gyr^{-1})$
$^{187}Re/^{187}Os$	0.0159(+0.0005, -0.0004)	
$^{232}Th/^{238}U$	0.0495 (+0.0000, -0.0000)	0.1551 (+0.0002, -0.0002)
$^{235}U/^{238}U$	0.985 (+0.009, -0.009)	0.1551 (+0.00002, -0.00002)
$^{244}Pu/^{238}U$	8.47 (+0.27, -0.27)	0.1551 (+0.0002, -0.0002)
Pair	$R(i,j)$	$\Delta^{max}(Gyr)$
$^{187}Re/^{187}Os$	1.03-1.23	1.8-13.4
$^{232}Th/^{238}U$	0.65(±0.09)	4.1 (+1.4, -1.2)
$^{235}U/^{238}U$	4.7 (+1.3, -0.9)	1.9 (+0.3, -0.3)
$^{244}Pu/^{238}U$	112 (+138, -92)	0.57 (+0.12, -0.21)

B. Th/U

Beta-decayed fission is the cause of the largest amount of uncertainty in $^{232}Th/^{238}U$ production ratio. The calculations of Thielmann et al. give 1.4 as the production ratio. The calculations of Meyer et al. (1985) give less delayed fission and, hence, suggest a higher production ratio. Although Meyer et al. do not include barrier penetration in their calculations, a fact which suggests that their production ratios may be too large, their results seem to be favored by Hoff's (1986) study of yields from thermonuclear explosions. The implication appears to be that less delayed fission occurs than that given by Thielmann et al. We thus conclude that Meyer and Schramm's use of the Thielmann et al. value of 1.4 as a lower limit on the Th/U production ratio is justified. With the probability of some β-delay fission, 1.7 is probably a reasonable upper limit with 1.55 as a good compromise. They also argue from terrestrial isotopic lead ratios and meteoritic ratios that the present solar system value for $^{232}Th/^{238}U$ is 3.9 ± 0.2. The relevant decay rates are $\lambda_{232} = 4.95x10^{-11}yr^{-1}$ (Jaffey et al. 1971).

C. U/U

Meyer and Schramm choose the Schramm and Wasserburg production ratio range $1.5^{+0.4}_{-0.3}$ as the best range for $^{235}U/^{238}U$. The range contains the Thielmann et al. value of 1.24.

The $^{235}U/^{238}U$ abundance ratio is well-known. Meyer and Schramm take it to be $1/(137.88 \pm 0.14)$. $\lambda_{235} = (9.8485 \pm 0.0135)x10^{-10}yr^{-1}$ (Jaffey et al. 1971).

D. Pu/U

The $^{244}Pu/^{238}U$ pair is the pair most affected by delayed fission. Meyer and Schramm use the Thielmann et al. value of 0.12 as a lower limit and the Symbalisty and Schramm upper limit 1.0 (no delayed fission) as an upper limit with 0.56 as a compromise best value. The abundance ratio is 0.006 ± 0.001 (Hudson et al.), although Meyer and Schramm note that the abundance ratio range may be more uncertain than this. $\lambda_{244} = 8.47 \pm 0.27x10^{-9}yr^{-1}$ (Fields et al. 1968).

Meyer and Schramm derive a range on t_ν/T of $0.43 \lesssim t_\nu/T \lesssim 0.59$. From this range and data from Table 1 for Th/U, we find a lower limit on T_{GAL} of 9.6 Gyr. Also, from the range $1.06 \lesssim R(187,187) \lesssim 1.14$, Meyer and Schramm derive an upper limit on T_{GAL} of 28.1 Gyr.

The range on t_ν/T agrees with the results of Hainebach and Schramm's (1977) study of detailed galaxy evolution models. In those models studied, Hainebach and Schramm found that steady synthesis seemed to be the best approximation to the chemical evolution of the Galaxy. Thus, $t_\nu/T = 0.50$ suggests itself as the best value. If we then use $t_\nu/T = 0.05$ and $\Delta^{max}_{232,238} = 4.1$ Gyr, the best value for Th/U from Table 1, we find $T \gtrsim 12.8$ Gyr. Use of $t_\nu/T = 0.05$ and $R(187,187) = 1.12$ gives $T \lesssim 19.8$ Gyr.

The best values range of $12.8Gyr \lesssim T_{GAL} \lesssim 19.8Gyr$ essentially agrees with other age estimates (e.g. Symbalisty and Schramm, Yokoi et al.). Yet, even though it is a relatively large range (7.8 Gyr), it does not include the allowed Galactic evolution models or input certainties. The range $9.6Gyr \lesssim T_{GAL} \lesssim 28.1Gyr$ includes the cosmochronological allowed galactic models and shows that the effect of these uncertainties is large. One may conclude from these results that nuclear cosmochronology, so simple in conception, is rendered quite difficult in practice because of input data uncertainties. It should be noted that any author who gives smaller ranges from nucleochronology is making some implicit assumptions about the chemical evolution of the Galaxy, and so, such ages are not pure nuclear dating. (They are also probably underestimating the uncertainty in the production rate determination process.)

Another recent input into the radioactive dating process has been the reported Th/Nd observations in stars (Butcher 1987). Unfortunately, the initial ages reported were very model dependent (Mathews and Schramm 1987). Since Nd is not a pure r-process nucleus, interpreting this ratio can be difficult. As Pagel notes, one might try to use a pure r-process nucleus instead of Nd to avoid this problem. Preliminary efforts at this type of analysis seem to yield relatively low ages $\lesssim 15Gyr$. Of course some have questioned the observation of Th itself, so it is still a bit premature to be forced to the short time end of the range for chronology. However, this is a development that should be watched and placed in the framework for consistency.

Consistency: A Scenario

The first point to note is that these four very independent techniques all yield ages that overlap in the 10 to 20 Gyr range. That such an agreement occurs at all is in some sense an independent confirmation of the basic Big Bang cosmological model!

At a more discriminating level, let us note that the best nucleochronologic models coupled with Galactic evolution as constrained by nucleochronology and the globular cluster ages tend to imply ages in the mid-teens. It is very difficult to get the oldest globular cluster to be $\lesssim 12Gyr$. Ages $t_u \gtrsim 12Gyr$ are consistent with $H_o \lesssim 85$ if $\Omega = 0$. However (ignoring walls for the moment), if $\Omega = 1$, such ages only are consistent with $H_o \lesssim 60km/sec/Mpc$. Furthermore, $H_o \gtrsim 40km/sec/Mpc$ is only consistent with $t_u < 17Gyr$ for $\Omega = 1$.

For overall consistency, most cosmologists would probably prefer a low value of H_o. Let us hope that with HST the H_o range converges to such values, otherwise we might be forced to such ugliness as a non-zero cosmological constant but tuned to an accuracy of parts in $\sim 10^{120}$ when measured in its natural (Planck) units or the exotic possibility of a domain wall dominated universe.

A universe with an age in the mid-teens (and a small H_o) still has to have disks form late if we are to be consistent with the white dwarf cooling argument. A several Gyr delay between the Big Bang and disk formation should tell us a lot about galaxy formation in general. If true, it would tend to argue against making galaxies as one large collapsing isolated system, but instead, it would require some disturbances to keep the disk from forming. One reasonable method to create such disturbances is collisions. Perhaps the earliest condensations were not of galaxy size but smaller. These proto-galaxies collapsed and made stars which started both the nucleochronology clock and the globular cluster clock, but not the disk closk. A high density of these proto-galaxies as implied by Tyson's observations would yield a high early collision rate. Such collisions would prevent disk formation. Eventually the density of objects would drop and collisions would cease so that the large merged galactic mass clumps would be able to form disks. Note that in this scenario stars formed in the proto-galaxies would naturally end up in the halo of the final galaxy. If such stars formed with a mass function peaked either higher or lower than the one in our disk, then one could produce lots of black holes or brown dwarfs in the halo. This could result in significant baryonic-dark halos. We further note that globular clusters could be proto-galaxies that never fully merged. This could yield a range in age for globulars from the first objects formed to the time when collisions stopped.

Obviously, much work remains in fleshing out this scenario, but the basic picture seems to hold together. Independent of this picture, it does seem that an age of 12 to 17 Gyr for our universe is still quite reasonable. (If H_o would ever be proven to be $\gtrsim 70 km/sec/Mpc$, it might force us to take seriously wall-dominated models.)

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